Confronting cold dark matter cosmologies with strong clustering of Lyman break galaxies at $z \sim 3$

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ABSTRACT

We perform a detailed analysis of the statistical significance of a concentration of Lyman break galaxies at $z \sim 3$ recently discovered by Steidel et al., using a series of N-body simulations with $N = 256^3$ particles in a $(100h^{-1}\text{Mpc})^3$ comoving box. While the observed number density of Lyman break galaxies at $z \sim 3$ implies that they correspond to systems with dark matter halos of $\lesssim 10^{12}M_\odot$, the resulting clustering of such objects on average is not strong enough to be reconciled with the concentration if it is fairly common; we predict one similar concentration approximately per $(6 \sim 10)$ fields in three representative cold dark matter models. Considering the current observational uncertainty of the frequency of such clustering at $z \sim 3$, it would be premature to rule out the models, but the future spectroscopic surveys in a dozen fields could definitely challenge all the existing cosmological models *a posteriori* fitted to the $z = 0$ universe.

Subject headings: cosmology: theory – dark matter – galaxies: clusters: general – method: numerical

1. Introduction

While currently many cosmological models are known to be more or less successful in reproducing the structure at redshift $z \sim 0$, this may be largely because there are still several degrees of freedom or *cosmological parameters* to appropriately *fit* the observations at $z \sim 0$, including the density parameter, Ω_0, the mass fluctuation amplitude at the top-hat window radius of $8h^{-1}$Mpc, σ_8, the Hubble constant in units of $100\,\mathrm{km\,s^{-1}Mpc^{-1}}$, h, and even the cosmological constant λ_0. This kind of *degeneracy* in cosmological parameters among viable models can be broken by combining the data at higher z (e.g., Jing & Fang 1994; Eke, Cole, & Frenk 1996; Barbosa et al. 1996; Fan, Bahcall, & Cen 1997; Kitayama, Sasaki & Suto 1998). This is why recent very deep surveys of galaxies, which have significantly advanced our understanding of the properties and distribution of galaxies at high redshifts, are equally important in constraining the underlying cosmological models.

Recently Steidel et al. (1997; S97 hereafter) reported a discovery of a highly significant concentration of galaxies on the basis of the distribution of 78 spectroscopic redshifts in the range $2 \le z \le 3.4$ for photometrically selected "Lyman break" objects. This discovery is quite important as discussed above, and therefore in this *Letter* we focus on exploring its impact on models of cosmic structure formation, specifically in the context of the cold dark matter (CDM) cosmologies.

S97 have already considered implications of their discovery on the basis of simple analytic models, and found that the objects are associated with spatially highly biased dark halos of mass $M \sim 10^{12} M_\odot$ which confirms earlier suggestions based on different grounds that the Lyman break galaxies are the progenitors of present massive galaxies (Steidel et al. 1996; Mo & Fukugita 1996; Baugh et al. 1997). We examine the theoretical impact of their discovery in much greater detail using a large number of mock samples from N-body simulations. Thus our analysis presented below properly takes account of several important and realistic effects including (i) the survey volume geometry, (ii) redshift-space distortion, (iii) selection function of the objects, (iv) fully nonlinear evolution of dark halos, and (v) finite sampling effect. As a result, we are able to predict simultaneously the number density of such objects and their clustering feature, and therefore can discuss the statistical significance of their discovery.

2. Simulation and selection procedure for "Lyman break" galaxies

The simulations have been performed with the $\mathrm{P^3M}$ code (Jing & Fang 1994) which now has been optimized for the vector processor. We consider three cosmological models summarized in Table 1, and run three different realizations for each model. The initial conditions are generated using the CDM transfer function of Bardeen et al. (1986) which is fixed by the shape parameter $\Gamma = \Omega_0 h$. The three models, the standard CDM (SCDM), a flat low-density CDM (LCDM), and an open CDM (OCDM) we have chosen are consistent with the abundance of low-redshift rich clusters (Kitayama & Suto 1997), and are also very close to those studied by S97. All the

simulations employ 256^3 ($\approx$ 17 million) particles in a $(100h^{-1}\mathrm{Mpc}\ )^3$ comoving box and start at redshift $z_i = 36$. The gravitational softening length ϵ is $39h^{-1}$kpc (comoving), and the mass of a simulation particle m_p is $1.7 \times 10^{10}\Omega_0 h^{-1} M_\odot$, both of which are small enough to resolve reliably the halos of Lyman break galaxies $\sim 10^{12} M_\odot$.

We identify halos of galaxies using the Friend-Of-Friend (FOF) algorithm with a bonding length 0.2 times the mean particle separation, and assume that each halo corresponds to one Lyman break galaxy. Although this procedure is fairly idealized, it is definite in the sense that the selected objects are characterized only by the threshold mass of the halos, and provides a reasonable approximation in examining the clustering feature of the resulting objects as a function of the halo mass. The robustness of our result to the identification procedure shall be discussed in §3.

Figure 1 plots the volume-averaged two-point correlation functions in real space $\bar{\xi}(R; M, z)$ of the halos with mass larger than M at redshift $z = 2.9$. Here and throughout the *Letter*, the error bars are calculated from the scatter among three realizations for each model. Figure 1 indicates that over the scales of interest the correlation functions of halos are enhanced approximately by a constant factor $b^2(M, z)$ relative to those of the dark matter. While this basic feature has been known previously (e.g, Mo, Jing & White 1996), Figure 1 clearly demonstrates the unprecedented quality (high mass resolution and large volumes) of our simulated halo catalogues which is essential in the statistical discussion below. Figure 2a plots this effective bias parameter for halos with mass larger than M, $b(> M) \equiv \sqrt{\bar{\xi}(R; M, z)/\bar{\xi}_{\mathrm{mass}}(R; z)}$, calculated at $R = 7.5h^{-1}$Mpc and $z = 2.9$, where $\bar{\xi}_{\mathrm{mass}}(R; z)$ is the volume-averaged correlation function of all *particles* in the simulations.

3. Statistical analysis with mock samples

The field, SSA22, reported by S97 covers 8.74×17.64 arcmin^2 sky area at $\alpha = 22^h 17^m$ and $\delta = +00°15'$. There are a total of 181 objects with magnitude $\mathcal{R} \leq 25.5$ which satisfy their color selection criteria. From their follow-up spectroscopic observations, it turns out that about 70 percent of the objects (i.e. about 130 objects in the field) are galaxies at $2 \leq z \leq 4$. They have measured redshift for 67 galaxies, which shows a strong concentration of 15 galaxies in one $\Delta z = 0.04$ bin at $z = 3.1$. In this section, we perform the statistical analysis with mock samples to examine the extent to which the CDM models can reproduce such a concentration. In generating the mock samples, we adopt a redshift selection function which is spline-interpolated from the redshift distribution histogram of Figure 2 of Pettini et al. (1997) and then normalized so as to have 130 galaxies in SSA22. Our resulting redshift selection function is approximately the same as that given by S97 when normalized to the same number of galaxies.

Between redshifts 2 and 4, each of our realizations has 7 outputs with time intervals $\Delta \ln(1 + z) = 0.1$. For a given threshold of the halo mass, we combine these outputs at different epochs with periodic replications to generate the mock samples of the SSA22 field. The peculiar

velocity and cosmological distortion effects on the distance - redshift relation (Matsubara & Suto 1996) are taken into account self-consistently in computing each redshift of the mock galaxies. The sky area of each mock field is fixed to be the same as that of SSA22, and halos inside each mock field are selected randomly according to the redshift selection function described above. Finally we randomly pick up 67 objects to mimic their spectroscopic observation. A total of 12,000 mock samples are generated for a given threshold of the halo mass in each model.

The mean number density of halos of mass larger than M (without applying the selection function) is plotted in Figure 2b. Three horizontal lines indicate the observed number density of Lyman break galaxies corresponding to our three model parameters. Note that the observed number density should be regarded as a strictly lower limit since some fraction of the galaxies might have been unobserved due to the selection criteria. Since the density of halos falls below the observed one for $M > M_{max}$, we vary the threshold mass of the halos from $10m_p$ up to M_{max} in considering the statistical significance of the clustering. We use a simple algorithm to identify a galaxy concentration in the mock sample following the procedure of S97; for each mock sample, we count galaxies within redshift bins of $\Delta z = 0.04$ centered at each galaxy and identify the redshift bin with the maximum count as the density concentration. Then we compute the probability $P_{\geqq 15}(M)$ that a mock sample has a concentration with at least 15 galaxies. Figure 2c indicates that the probability $P_{\geqq 15}(M)$ increases with the halo mass as expected, since the clustering is stronger for more massive halos. For the halo mass $M \lesssim 10^{11}h^{-1}M_{\odot}$, $P_{\geqq 15}(M)$ is less than 5 percent for all the three models. The probability $P_{\geqq 15}(M)$ can increase to 15% for LCDM and OCDM, and to 10% for SCDM at M_{max}.

The above conclusion might be dependent on the value of σ_8 which we fixed for each model. In the case of SCDM with $\Gamma = 0.5$, we can study its dependence by analyzing the simulation outputs at different epochs. Figure 3 plots the probability $P_{\geqq 15}(M_{max})$, i.e., the maximum probability as a function of σ_8. The probability is about 10% for $\sigma_8 \leq 1.2$ which is the value suggested by the 4yr COBE data for the Harrison - Zel'dovich primordial spectrum in this model.

Since the identification of "galaxies" from pure N-body simulations is not totally unambiguous, we have carefully examined if our results are sensitive to the particular identification procedure adopted here. First we tried another identification scheme in which those spherical regions around each potential minimum with overdensity above $178\Omega_0^{-0.6}$ are defined as halos. It has been shown that this scheme removes some problems of the FOF method (e.g., Jing & Fang 1994). With such selected dark halos, we repeated our procedure and found that the resulting $P_{\geqq 15}(M)$ agrees within 2% with that based on the FOF halos. Thus, provided that one dark halo corresponds to one galaxy, our results presented above are quite robust.

Another critical question is the over-merging effect: one virialized halo in principle may harbor more than one galaxy. If this were the case with the observed Lyman-break galaxies, our analysis would under-predict the probability $P_{\geqq 15}$. However this seems to be very unlikely; among the 15 galaxies in the concentration of S97, there are only two pairs of galaxies with a sky

separation less than $1'$ ($\approx 1h^{-1}$Mpc in comoving). Both pairs have a radial velocity difference about $2000\,\mathrm{km\,s^{-1}}$ (in the rest-frame at $z = 3.1$), so it is not likely that each pair is in the same virialized halo (note that at z about 3, rich clusters with a velocity dispersion about $2000\,\mathrm{km\,s^{-1}}$ are very rare in CDM models). We have also checked our mock samples directly and found that each high concentration on average has 3 pairs of mock galaxies closer than $1'$ in all the three models we considered, which agrees with the observation. This indicates that if we further break virialized halos into mock galaxies, we would have too many close pairs. To be more specific, we have experimented this procedure for the OCDM simulations by identifying halos with FOF at a much earlier epoch $z \approx 6$, placing mock galaxies to the center particle of each halo, and assuming all these mock galaxies survive until the observed redshift (i.e., no later merger). In this case the probability $P_{\geqq 15}(M_{max})$ is nearly doubled, but there are on average about 7 pairs of galaxies closer than $1'$ in each high concentration, which is much higher than that observed. Therefore it appears that the over-merging effect does not significantly bias our result.

Considering the fact that S98 observed the concentration in their *first* densely-sampled field, it seems that the CDM models are only marginally consistent with the observation depending on its statistical significance.

4. Conclusions

We have carried out a detailed analysis of the statistical significance of a concentration of galaxies at $z \sim 3$ discovered by S97 based on mock samples constructed from a series of N-body simulations. The observed number density of Lyman break galaxies at $z \sim 3$ implies that they correspond to systems with dark matter halos of $\lesssim 10^{12} M_{\odot}$, as suggested by Steidel et al. (1996). While the clustering of such objects is naturally biased with respect to dark matter, the predicted bias $1.5 \sim 3$ is not large enough to be reconciled with such a strong concentration of galaxies at $z \sim 3$ if one similar structure is found per one field on average; we predict one similar concentration approximately per ten fields in SCDM and per six fields in LCDM and OCDM. Our procedure is definite and reliable in the sense that it is derived from the mock samples which adopt all the realistic effects relevant to the statistical discussion. Our conclusions are qualitatively consistent with those of S97, but in fact much more stringent mainly because we simultaneously consider the constraints from both the observed number density of objects and their clustering; the predicted number density of the more biased halos, which is consistent with the strong concentration, is too small to be compatible with the observed one. Although it would be premature to rule out the models discussed here, we have clearly demonstrated the importance of deep surveys of galaxies in constraining the cosmological models; future spectroscopic surveys in a dozen fields (Pettini et al. 1997) could challenge all the existing cosmological models *a posteriori* fitted to the $z = 0$ universe.

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Table 1. Simulation model parameters

Model	Ω_0	λ_0	Γ	σ_8	m_p ($h^{-1}M_\odot$)
SCDM	1.0	0.0	0.5	0.6	1.7×10^{10}
OCDM	0.3	0.0	0.25	1.0	5.0×10^{9}
LCDM	0.3	0.7	0.21	1.0	5.0×10^{9}

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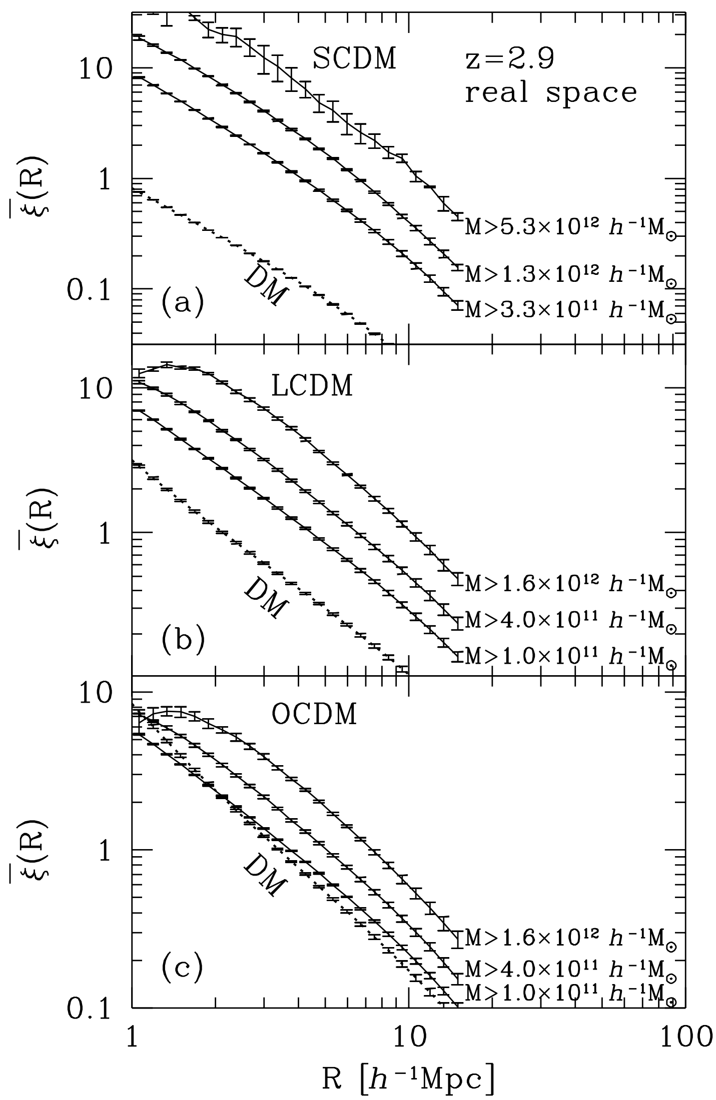

Fig. 1.— Two-point correlation functions of halos at $z = 2.9$ in real space; different curves correspond to the different threshold masses M of the halos in (a) SCDM, (b) LCDM, and (c) OCDM models. Curves labeled by DM correspond to the correlation functions of all particles in the simulation.

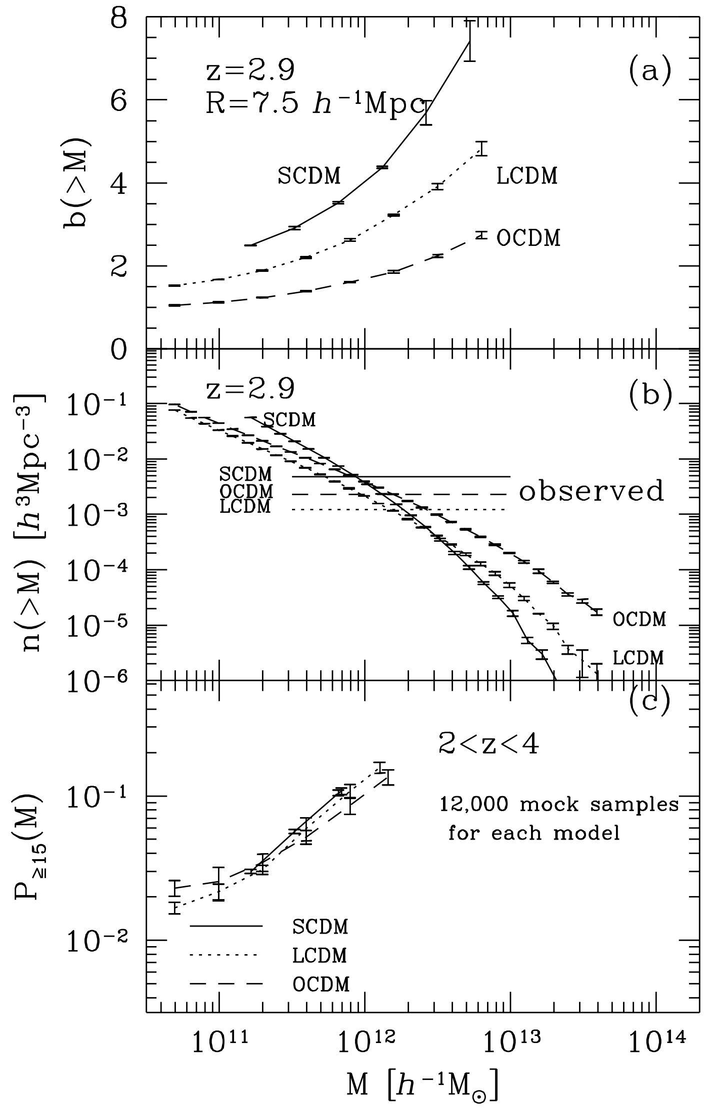

Fig. 2.— Statistics of the halos as a function of the threshold mass; (a) bias parameter of halos at $z = 2.9$; (b) mean number density of halos in the simulations compared with the observed one of Lyman break galaxies; (c) probability of finding a concentration of at least 15 halos in a bin of $\Delta z = 0.04$.

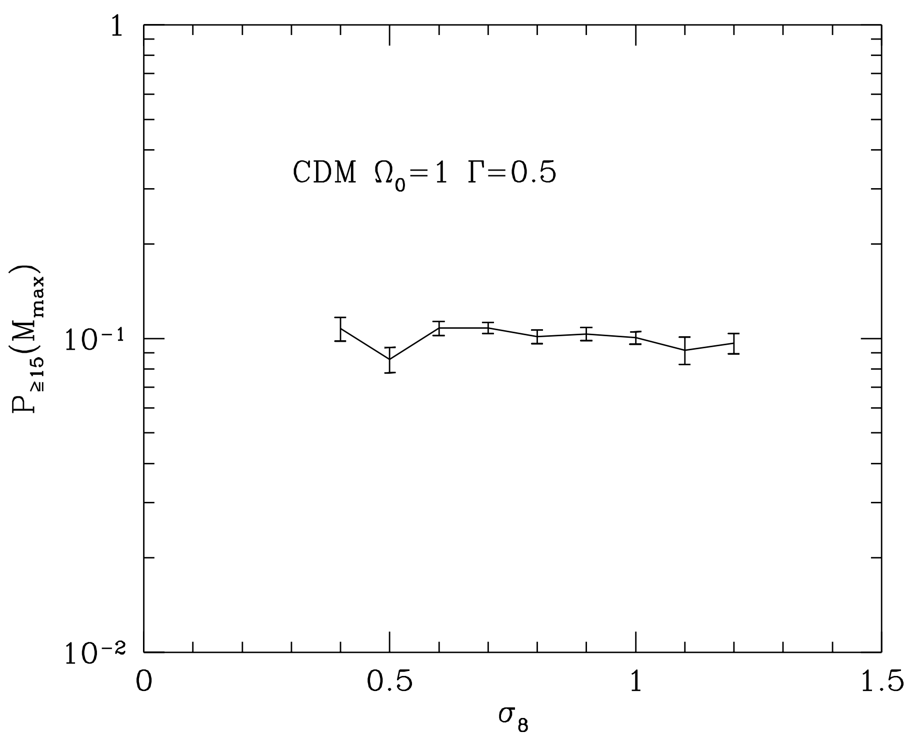

Fig. 3.— Maximum probability $P_{\geqq 15}(M_{max})$ in SCDM ($\Gamma = 0.5$) as a function of σ_8.